Determining of the material parameters of $Zn_xCd_yHg_{1-x-y}Te$ by the magnetophonon spectroscopy

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ABSTRACT

The phonon and electron subsystems were studied in quaternary solid solutions of $Zn_xCd_yHg_{1-x-y}Te$ (ZMCT) by means of Raman scattering and Magnetophonon Resonance. The Raman spectra of several compositions confirm the three-mode behaviour of phonon spectra. The cluster mode has also been observed. Four kinds of LO-phonons (of HgTe-like, CdTe-like and ZnTe-like sublatticies and ZnTe-clusters) participate in the electron-phonon interaction. Four types of one-phonon Magnetophonon Resonances and two types of Magnetophonon Resonances on the difference of phonon frequencies have been observed.

Keywords: magnetophonon resonance, semiconductors

1. INTRODUCTION

Random homogenous substitutions of matrix cations by another metal atoms in the solid solution lattices with common anion (as is the case in GaAs-AlAs or HgTe-CdTe) is known to cause a continuous reconstruction of the electronic structure and the phonon spectra with composition variation. It may be assumed that the introduction of a third cation will enable us to obtain a supplementary degree of freedom in the control of material parameters. It has an additional advantage in the case of HgTe-CdTe (MCT), because the introduction of Zn-atoms stabilises the weak Hg-Te bonds in crystal lattice of this solid solution, whereas he presence of Cd-atoms destabilises them [1-3]. The introduction of the fourth component Zn causes not only a simple extension of the physical properties of MCT, but also new phenomena, connected with multimodeness of the crystal lattice. 'Multimodeness' is an issue of primary significance in the study of four-component solid solutions. ZMCT has three sublattices (ZnTe-like, CdTe-like and HgTe-like). Therefore, a three-mode behaviour of the phonon spectrum in this solid solution may be predicted. Other possibilities also exist [4].

The present article discusses of ZMCT structures investigated of ZMCT by means of Magnetophonon Resonance (MPR) experiments, a powerful tool for the investigation of electron and hole spectra [5].

A series of films of ZMCT obtained by liquid-phase epitaxy on CdTe substrates have been studied. The thickness of homogeneous layers is d = 4μm. The temperature dependencies of electroconductivity and Hall coefficient measured in those structures have shown an activated behaviour. The quality of epitaxial layers investigated by MPR is comparable with the corresponding high quality MCT alloys with the same energy gap (near 180 - 300 meV). The mobility of electrons in those layers is sufficiently high to observe the MPR. It is important to note that the parameters of these samples have not changed over the period of three years, whereas MCT samples are characterised by the temporal degradation of parameters.

2. EXPERIMENTAL RESULTS

MPR was observed on three samples: IV,V and VI. The measurements were performed in pulsed magnetic fields. The second derivation of transverse magnetoresistance $d^2\rho_{xx}(B)/dB^2$ as a function of a magnetic field B was registered up to 6.5 T at different temperatures within the range of 77 - 200 K. The most detailed investigations were performed for sample IV. The experimental records obtained for this specimen at different temperatures are shown in Fig. 1.

When the temperature was increased above 124 K, a group of strong peaks (a wide maximum) appears in the range from 2.0 to 3.8 T; the corresponding harmonics were at 1.0 -1.9 T and 0.6 -0.9 T. The peak $a1^+$ is the strongest and the most distinguishable for the range 124 K≤ T ≤ 158 K, whereas peak $a1^-$ is most distinguishable at T > 158 K.

These peaks are correspondent to their harmonics $a2$, $a3$ and $a4$, are observed in the fields approximately equal to 1/2 B_0, 1/3 B_0 and 1/4 B_0, respectively (B_0 - resonance magnetic field for peak $a1^+$).

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In this manner three other series of peaks can be determined - *b*, *c* and *k*. Therefore, the structure of wide maximums – which are clearly visible on experimental curves in Fig.1 at temperatures above 124 K – corresponds to four series of peaks. These series are connected with four kinds of phonons.

A similar investigation has been conducted for specimens V and VI, for which x+y is significantly larger and, correspondingly, the effective mass of electrons is also greater. Consequently, the whole system of resonances is shifted to higher magnetic fields.

From these general considerations it follows that the series *a* is caused by the absorption of LO-phonons of HgTe-like sublattice, since these phonons have the lowest energy and they are present in the greatest numbers in the lattice of ZMCT. However, the energy of the LO-phonons which can participate in electron-phonon interaction in this lattice have to be determined for the correct interpretation of MPR-s data.

The LO-phonon frequencies for HgTe-like, CdTe-like, ZnTe-like sublattices as well as ZnTe-binary clusters were determined from Raman Spectra and far-infrared reflection spectra in our previous paper [6]. The frequencies and energies of LO-phonon for measured samples are given in Table 1.

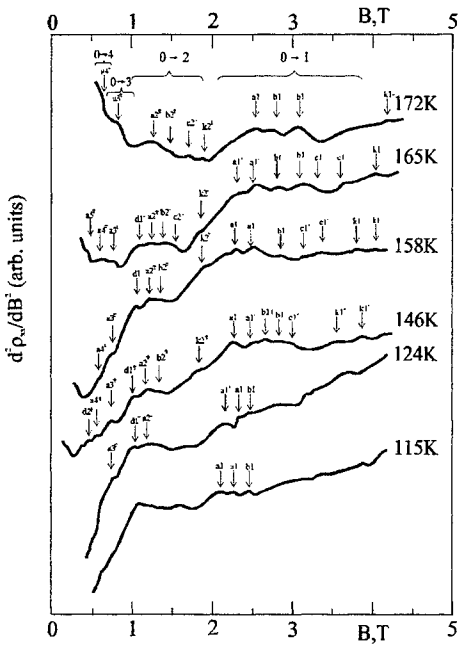

Fig. 1 Experimental records of $d^2\rho_{xx}(B)/dB^2$ obtained for sample IV at different temperatures.

Table 1. Values LO(Γ)-phonons frequencies and energies for compositions IV,V and VI.

composition	HgTe-like mode	CdTe-like Mode	ZnTe-like Mode	ZnTe-cluster
IV ω_{LO},cm^{-1}	137	156.0	171.5	198.0
$\hbar\omega_{LO}$, meV	17.0	19.3	21.3	24.6
V ω_{LO}, cm^{-1}	136.0	156.0	174.0	198.0
$\hbar\omega_{LO}$, meV	16.8	19.3	21.7	24.6
V I ω_{LO}, cm^{-1}	136.0	156.0	175.0	198.0
$\hbar\omega_{LO}$, meV	16.8	19.3	21.9	24.6

It follows from the considerations above that peaks $a1^+$ and $a1^-$ - the strongest and the most distinguishable at T > 124 K on experimental curves in Fig. 2 - 4 and characterised by harmonics at corresponding magnetic fields – are caused by electron transitions 0^+ - 1^+ and 0^- - 1^- accompanied by absorption of LO-phonons of HgTe-like sublattice. Our further interpretation of MPR-spectra is based on this assumption which enables us to estimate to the first approximation the parameters of the band structure using the energy value of LO-phonon of HgTe-like sublattice from Table 1 and experimental positions in magnetic field of peaks $a1^+$ and $a1^-$.

3. THE BAND STRUCTUERE PARAMETERS

The band structure parameters have been calculated according to R. Aggrawal's version [7] of the Pidgeon-Brown model [8]. This method is based on the three-level Kane's model [9].

The experience has shown that the choice of the values of the Luttinger valence-band parameters γ_1^L, γ_2^L, γ_3^L and K^L is crucial to the determination of the band structure parameters for MCT [10-12] using the relations between them given below:

$$\gamma_1^L = \frac{E_P}{3E_g} + 2.5\,,\quad \gamma_2^L = \gamma_3^L = \frac{E_P}{6E_g}\,. \qquad (1)$$

It has been assumed that E_P = 18.0 eV and Δ = 1.0 eV [10] and they do not depend on the temperature and composition. According to [13], the next parameter K^L should be represented as follows:

$$K^L = \gamma_3^L - \frac{1}{3}\gamma_1^L + \frac{2}{3}\gamma_2^L - \frac{2}{3} - \frac{5}{4}\delta_{exch}, \quad (2)$$

where $\delta_{exch.}$ stands for the correction for the nonlocality of the potential and is equal to 0.4 for MCT [13]. As for the parameter F, representing the interaction of the conduction band with the upper bands, we have used the value F = -0.5 determined by Weiler et al. [10]. We have assumed that this parameter is also not dependent on the temperature and composition.

4. THE DETERMING PROCEDURE OF THE BAND STRUCTURE PARAMETERS

In order to calculate the theoretical positions of MPR-s peaks, we applied the best fit procedure to the experimental positions of peaks $a1^+$ and $a1^-$ and thus obtained the value of energy E_g = 190 meV at obtained temperature: T = 146K. The next step of the calculation procedure is to fit the theoretical positions of all the observed peaks *a*-series to the experimental ones at a given temperature. The best fittings are shown in Fig. 2 for T = 146 K and Fig. 3 for T = 165 K, where electron transitions corresponding to resonance peaks of series *a* are shown by solid lines. We can state a good agreement between experimental and theoretical positions of resonances (the average discrepancy for eight peaks of series a^+ and a^- on the curve at 146 K is equal to approximately 1.5%). The thus - obtained band parameters for T = 146 K and 165 K are shown in Table 2.

Now, it is possible to interpret the other series of peaks, namely: *b, c* and *k*. Since the positions of peaks $b1^+$, $c1^+$and $k1^+$ are characterised by an increase in magnetic field, these peaks may be expected to be caused by electron transitions 0^+ - 1^+ with the assisted absorption of LO-phonons of, consequently, increasing frequencies. This sequence of increasing frequencies corresponds to the LO-phonons in CdTe-like, ZnTe-like sublattices and ZnTe-clusters. The theoretical positions of MPR for all series were calculated using the aforementioned band-structure parameters and phonon energies (Table 1).

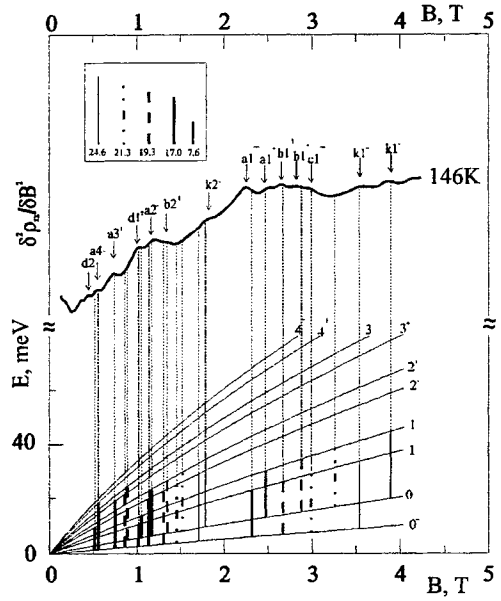

Fig 2.Experimental record of $d^2\rho_{xx}(B)/dB^2$ obtained for sample IV at temperature 146 K. The electron transitions between Landau levels corresponding to the observed MPR's are shown lower. The inset shows the appropriated phonon energies or difference of phonon energies (the values are given in meV).

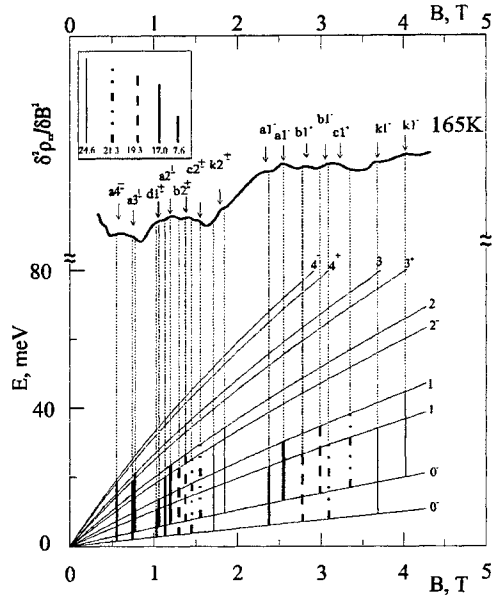

Fig. 3 Experimental record of $d^2\rho_{xx}(B)/dB^2$ obtained for sample IV at temperature 165 K. The electron transitions between Landau levels corresponding observed MPR's are shown lower. The inset shows the appropriated phonon energies or difference of phonon energies (the values are given in meV).

Table 2. The band-structure parameters values for sample IV–VI.

Parameters	sample IV 146 K	sample IV 165 K	Sample V 106 K	sample VI 99 K
E_g, meV	192	205	320	350
E_P, meV	18000	18000	18000	18000
γ_1^L	33.75	31.7	21.25	19.64
$\gamma_2^L = \gamma_3^L$	15.62	14.6	9.38	8.57
K^L	13.62	12.6	7.38	6.57
F	-0.5	-0.5	-0.5	-0.5
Δ, meV	1000	1000	1000	1000

The overall representation of the electron transitions which interpret the observed MPR peaks may be found in Fig.2, 3. It shows that the suggested interpretation of MPR's peaks based on the application of four kinds of LO-phonons is in good agreement with the experimentally observed structures of the resonance curves. Simultaneously, the quantitative agreement between calculated positions of corresponding electron transitions in the magnetic field and observed peaks of four series is within the range of about 1.5% (measurement accuracy of resonance fields is ~3%). The comparison of the two curves (the first one at 146 K and the second at 165 K) reveals that the increase in the temperature is accompanied with the increase of amplitudes of the peaks $a1^-$ and $a2^-$. This observation is also made for the peaks of another series caused by electron transitions between 0^- and N^- Landau levels. It is obvious enough that the increase of temperature causes the increase of the electron occupation of 0^- Landau level and the increase in the amplitude of the aforementioned peaks. Nevertheless, the peaks of series *d* in the small magnetic fields are hardly visible at temperatures higher than 124 K (for sample IV).
The same method of the band-structure parameters calculation and the interpretation of MPR's peaks using phonon energies as represented in Table 1 is applied to the samples V and VI. The values of the band -structure parameters determined for these samples from MPR data are represented in Table 2.

5. CONCLUSIONS

Temperature dependence of energy gap $E_g(T)$ and effective mass of the conductivity electrons $m_c(T)$ calculated with help of the temperature shift of MPR peaks for two samples ZnCdHgTe (II and V) are presented in Fig. 5 and 6. It is shown that increasing of ZnTe contains in solid solutions leads to decreasing of value of the coefficient dE_g/dT. That means it is possible to obtain ZnCdHgTe solid solutions with nondependent on temperature band-structure parameters.

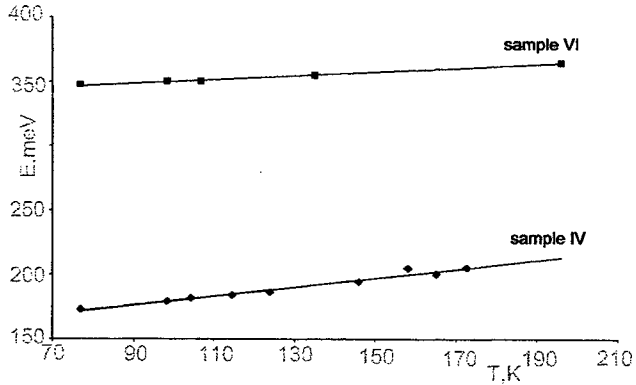

Fig 4. The temperature dependence of the energy gaps.

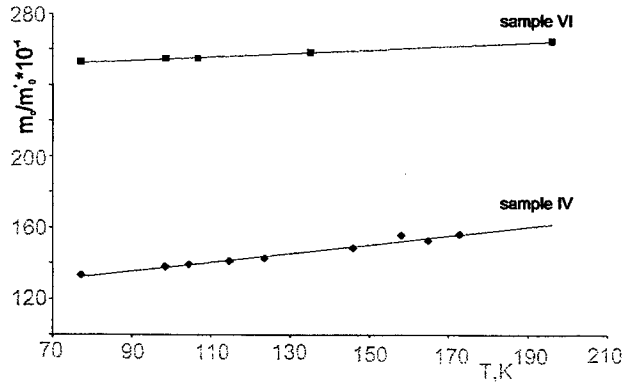

Fig 5 The temperature dependence of the effective masses.

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